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By Martha B. Shapley.

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Read by Title November 9, 1932.

A large number of observations of eclipsing variable stars have been made from plates of the Harvard photographic collection by Mrs. Esther Robinson, working under a grant to Dr. Harlow Shapley from the Permanent Science Fund administered by the American Academy of Arts and Sciences. Mrs. Robinson has had much experience in the estimation of the brightness of variable stars on photographic plates, and the light curves that have been derived from her measures are of considerable accuracy, apparently as satisfactory as can be obtained from in-focus photographic images.

The light curves derived from the observations were placed at my disposal for the calculation of the orbital elements and for general discussion of the various characteristics of the binary systems. The present communication gives the results for RW Arae and SW Ophiuchi, two systems which have in common the character of constant maximum light, with a barely measurable indication of a secondary eclipse. The light curves for these binaries show no trace of ellipticity or reflection effects.

RW Arae. The variability of RW Arae was discovered by Miss Cannon in 1910 and an approximate period determined. The new photographic observations, derived from 866 plates of the Harvard collection, permit the revision of the formula for primary minimum as follows:

$$\text{minimum} = \text{J. D. } 2419755.6911 + 4^{d}.3675094\text{E} \pm 0.0000025\text{E (p. e.)}$$

In the course of the discussion of the normal points and supernormal points I have adjusted the initial epoch which was used in the least squares solution for the light elements so as to have it coincide with the mid-point of primary minimum. Table I contains information concerning the comparison stars for both variables, and Table II gives data of a general nature for the variables themselves. The 866 observations for RW Arae have been grouped into the normal points in Table III; successive columns give the serial number of the normal with the number of observations, the mean phase computed with the elements given above, the mean

photographic magnitude, and the residuals from the theoretical light curves which I have derived from the computed orbital elements listed in Table IV. The first seventeen normal points from Table III refer to the primary minimum, and from fifty-two to sixty-three the normals fall in the region of secondary minimum. Since the exposure times average approximately one hour, the phases in the third column are geocentric.

The mean photographic light curve given by Table III has been satisfactorily represented. The star proves to be a binary system in which the bright component has about one-third the diameter of the faint star but is more than fifty times as bright per unit surface area. This conclusion is based on the hypothesis of complete darkening toward the limb according to the usual cosine law. An alternative solution, assuming uniform distribution of light over the disk of the star, gives a binary system in which one component is only a sixth the diameter of the other but has five-sixths the total light of the system. Thus the conception of uniform brightness is less satisfactory than the hypothesis of complete darkening.

The two computed curves for RW Arae are shown in Figure 1 with the observations of primary minimum. In Figure 2 (a) all the normal points of Table III are given, together with the computed curve. The maximum is essentially flat, from which we conclude that the stars are spheroidal. There is in the observations a slight suggestion of a secondary minimum midway between the successive primaries, in agreement with the computed value of $0^m.01$. The maximum light observations preceding the secondary minimum show as a whole a brighter average magnitude than those between the secondary and the following primary. This phenomenon perhaps indicates that the preceding side of the bright component is brighter than its following side.

The principal characteristics of the RW Arae system are shown in diagram in Figure 2 (b): the components are well separated; the small bright star has about one and one-half times the diameter of the sun; the larger, fainter component has about five times the sun's diameter; and the inclination is relatively low for a total eclipse.

The orbital data for RW Arae, on the two assumptions of uniform distribution in brightness and total darkening at the limb, appear in Table IV. The semiduration of totality for "darkened" stars is but a third the duration of the alternative assumption and results in a rounded minimum and a slightly better fit to the observations. In

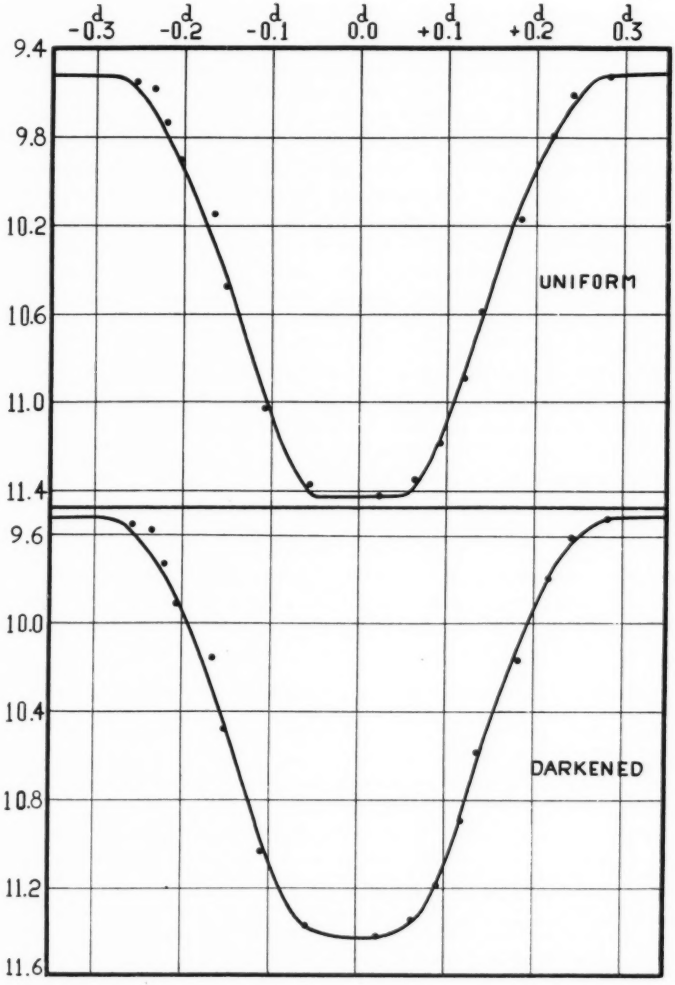

FIGURE 1. RW Arae: Computed curves and observations during primary minimum. Ordinates are stellar magnitudes.

the less probable "uniform" solution the bright star is exceptionally small compared with the fainter one, but its surface brightness is nearly one hundred and fifty times as great per unit area, indicating a high degree of density, but perhaps not abnormally so for a star of spectral class A0. With this exception the two solutions are similar. It should be noted that the absolute magnitude, M_2, of the component for which we have the spectral class, is within the range of values commonly found for spectrum A0; it should also be noted that the faint absolute magnitude and the low density of the large component emphasize the anomalous position of many of the dark components of eclipsing binaries in the spectrum-luminosity (Russell) diagram. Both the absolute magnitudes and the mean densities are accurately determined as to order of magnitude, notwithstanding uncertainty concerning other characteristics of the binary. But we should expect a star of the third magnitude (absolute) to have a mean density of at least one hundred times the value here computed. The spectral class of the large star unfortunately remains unknown; probably it is similar to that of the sun.

The symbols in Table IV are those conventionally used in the calculation of eclipsing star orbits, with subscript 1 referring to the larger, darker component.

SW Ophiuchi. The eclipsing variable SW Ophiuchi was also found at the Harvard Observatory. When announced in 1908 by Miss Leavitt an approximate period was given. The light elements, based on the new observations derived from 631 photographs, are as follows, after adjusting the initial epoch to the eclipse:

$$\text{minimum} = \text{J. D. } 2420740.4691 + 2^{d}.4459310\text{E} \pm 0.0000016\text{E (p. e.)}.$$

Information concerning the comparison stars and the variable itself has been given in earlier Tables. The sixty-seven normal points into which the observations have been assembled appear in Table V which follows the form of Table III described above. Normals one to twenty refer to primary minimum; forty-one to fifty to the region of the secondary minimum. Since the computed curves based on the uniform and darkened hypotheses are almost identical, the residuals, O—C, in Table V are given only for the uniform solution. The phases are heliocentric. Figure 3 shows the computed curves and observations during primary minimum; Figure 4 (a) gives the whole computed curve with the observed data, and (b) represents a diagram of the system. The maximum light observations indicate the absence

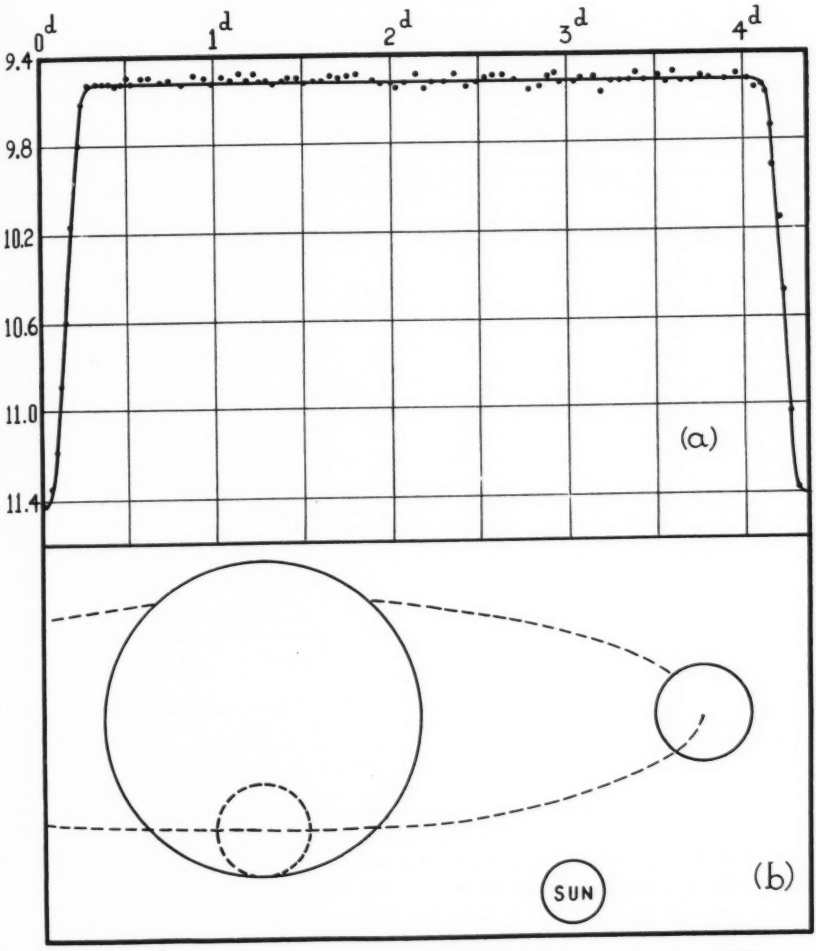

FIGURE 2. RW Arae: (a) Normal points from Table III, and computed curve. (b) Diagram of the system (darkened). Ordinates are stellar magnitudes.

of appreciable ellipticity and show faintly the secondary eclipse which is computed to be three hundredths of a magnitude.

The system of SW Ophiuchi consists of two stars the fainter of which has nearly twice the diameter of its bright companion, and

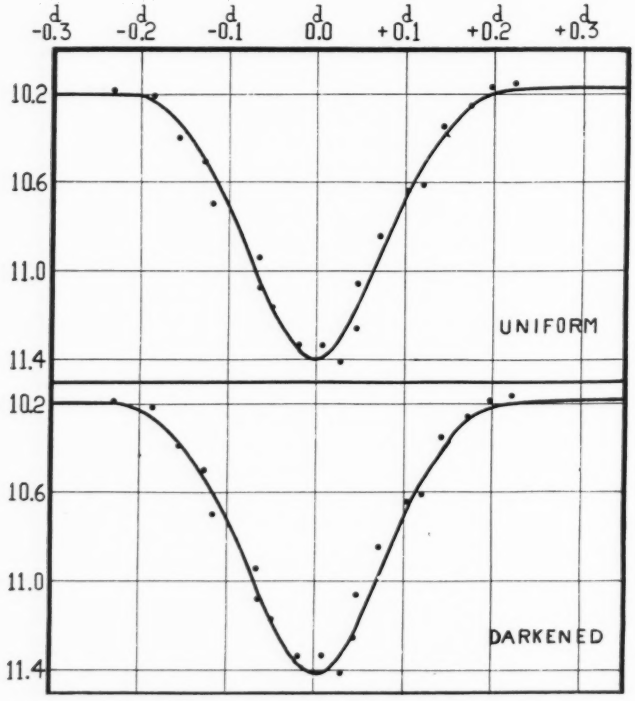

FIGURE 3. SW Ophiuchi: Computed curves and observations during primary minimum. Ordinates are stellar magnitudes.

both are considerably larger than the sun. It is a remarkably normal eclipsing binary, in size, orbit, density, magnitude, surface brightness, and parallax. The orbital data are given in Table VI in the usual form. Perhaps the most striking point in Table VI is the unusual

similarity of the uniform and darkened columns. The observations are equally well represented by the two hypotheses.

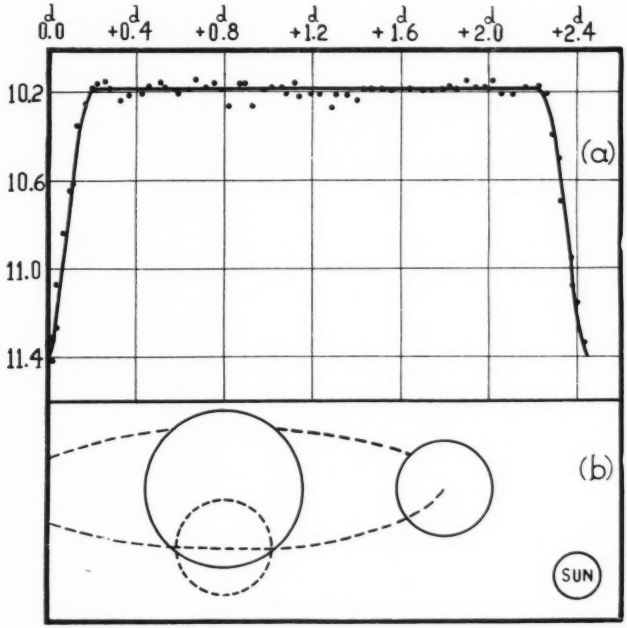

FIGURE 4. SW Ophiuchi: (a) Normal points from Table V, and computed curve. (b) Diagram of the system. Ordinates are stellar magnitudes.

Summary. The eclipsing binary RW Arae has been observed on 866 photographs from the Harvard collection and the material made the basis for the calculation of orbital elements and other data. The elements and the light curve show that there is a total eclipse involving two stars, well separated, differing considerably in size and surface brightness. The stars are spheroidal, and there is a slight secondary minimum. The assumption of a stellar disk darkened toward the edge agrees with the observations better than the alternative assumption of uniform brightness.

The low density combined with faint absolute magnitude of the large dark companion presents a puzzling phenomenon that is not observed among isolated stars and is in conflict with the usual views on the spectra and luminosities of stars.

Six hundred and thirty-one observations of the eclipsing variable SW Ophiuchi yield orbital data showing a system of fairly close stars partially eclipsing each other in a period of about two and a half days; the smaller and brighter component is three-fourths eclipsed at primary minimum. The uniform and darkened solutions are nearly identical and give results that are entirely normal in a binary of spectral class A0.

October 1, 1932.

TABLE I.

THE COMPARISON STARS.

Variable	Comparison Star	H.D.	R.A. 1900	Dec. 1900	Pg. Mag.	Spectrum
RW Arae	a	157559	$17^h\ 18^m.8$	$-57°\ 1'$	8.06	F0
	b	159236	17 28.4	−57 3	8.62	A0
	c	159020	17 27.2	−57 4	9.68	A0
	d		17 28.2	−56 52	10.65	F8
	e		17 25.9	−56 55	11.38	F5
	f		17 26.2	−56 57	11.60	too faint
SW Ophiuchi	a	147080	16 14.6	− 6 43	9.97	F8
	b	146623	16 12.1	− 6 26	10.51	F0
	c	146816	16 13.1	− 6 45	10.91	G5
	d		16 13.2	− 6 50	11.55	K

TABLE II.

GENERAL DATA ON THE TWO SYSTEMS.

	RW Arae	SW Ophiuchi
R.A. 1900	$17^h\ 26^m.3$	$16^h\ 11^m.1$
Dec. 1900	$-57°\ 5'$	$-6°\ 44'$
λ	302°	334°
β	−14°	+28°
Pg. mag. max.	9.52	10.19
Spectrum	A0	A0
Primary eclipse	total	partial
Shape of stars	spheroidal	spheroidal
No. of observations	866	631

TABLE III.

NORMALS OF RW ARAE WITH RESIDUALS FROM COMPUTED CURVES.

Number	Number of Observations	Mean Phase	Mean Magnitude	O—C U	O—C D
1	5	$-0^d.257$	9.55	$0^m.00$	$-0^m.03$
2	6	.234	9.58	− .10	− .10
3	4	.220	9.73	− .04	− .03
4	5	.205	9.91	+ .01	+ .01
5	5	.165	10.15	− .13	− .13
6	7	.151	10.48	+ .02	+ .02
7	5	.109	11.03	+ .05	+ .05
8	1	−0.057	11.37	− .04	− .01
9	2	+0.023	11.43	.00	.00
10	2	.063	11.35	− .03	− .01
11	4	.093	11.19	+ .03	+ .03
12	5	.119	10.89	+ .04	+ .01
13	5	.137	10.59	− .02	− .01
14	6	.181	10.17	+ .05	+ .05
15	7	.218	9.80	.00	.00
16	8	.241	9.61	− .01	− .03
17	6	.281	9.53	+ .01	.00
18	11	.321	9.52	.00	
19	11	.364	9.52	.00	
20	10	.396	9.52	.00	
21	10	.426	9.53	+ .01	
22	10	.464	9.52	.00	
23	11	.495	9.49	− .03	
24	10	.525	9.53	+ .01	
25	11	.579	9.50	− .02	
26	11	.630	9.50	− .02	
27	10	.690	9.52	.00	
28	10	.738	9.51	− .01	
29	11	.811	9.53	+ .01	
30	12	.880	9.49	− .03	
31	12	.945	9.50	− .02	
32	10	0.983	9.53	+ .01	
33	12	1.036	9.50	− .02	
34	10	.091	9.51	− .01	
35	10	.142	9.49	− .03	
36	10	.178	9.51	− .01	
37	11	.215	9.49	− .03	
38	11	.250	9.52	.00	
39	13	+1.291	9.51	−0.01	

TABLE III—*cont.*

Number	Number of Observations	Mean Phase	Mean Magnitude	O—C U	O—C D
40	11	$+1^d.334$	9.53	$+0^m.01$	
41	10	.378	9.51	− .01	
42	9	.419	9.50	− .02	
43	10	.470	9.50	− .02	
44	11	.512	9.53	+ .01	
45	11	.559	9.52	.00	
46	11	.607	9.52	.00	
47	10	.665	9.50	− .02	
48	10	.706	9.51	− .01	
49	10	.746	9.50	− .02	
50	10	.812	9.49	− .03	
51	10	.888	9.52	.00	
52	10	.945	9.53	+ .01	+0.01
53	12	1.988	9.53	+ .01	+ .01
54	10	2.032	9.55	+ .03	+ .02
55	10	.080	9.53	+ .01	.00
56	11	.136	9.49	− .04	− .04
57	10	.193	9.56	+ .03	+ .02
58	10	.234	9.53	.00	− .01
59	10	.303	9.53	+ .01	.00
60	11	.365	9.49	− .03	− .04
61	11	.433	9.55	+ .03	+ .03
62	10	.486	9.53	+ .01	+ .01
63	10	.534	9.51	− .01	−0.01
64	10	.583	9.50	− .02	
65	10	.641	9.50	− .02	
66	11	.708	9.52	.00	
67	11	.792	9.56	+ .04	
68	11	.835	9.55	+ .03	
69	11	.886	9.50	− .02	
70	10	.928	9.49	− .03	
71	10	2.965	9.53	+ .01	
72	10	3.040	9.53	+ .01	
73	10	.084	9.51	− .01	
74	10	.154	9.51	− .01	
75	10	.193	9.58	+ .06	
76	10	.246	9.53	+ .01	
77	12	.305	9.53	+ .01	
78	11	.347	9.53	+ .01	
79	10	+3.387	9.49	−0.03	

TABLE III—*cont.*

Number	Number of Observations	Mean Phase	Mean Magnitude	O—C U	O—C D
80	15	+3.445	9.53	+0^m.01	
81	10	.525	9.51	− .01	
82	11	.562	9.53	+ .01	
83	10	.605	9.49	− .03	
84	11	.653	9.53	+ .01	
85	10	.713	9.53	+ .01	
86	10	.761	9.51	− .01	
87	11	.807	9.52	.00	
88	12	.898	9.52	.00	
89	11	3.959	9.50	− .02	
90	10	4.024	9.53	+ .01	
91	10	+4.073	9.56	+0.04	

TABLE IV.

ORBITAL ELEMENTS OF RW ARAE.

	Uniform	Darkened
Range, primary	1^m.91	1^m.91
Range, secondary	0^m.006	0^m.015
t'	0^d.273	0^d.289
t''	0^d.051	0^d.017
M_1	+3.37	+2.61
M_2	+1.67	+0.91
m_1	11.43	11.43
m_2	9.73	9.73
L_1	0.172	0.172
L_2	0.828	0.828
J_2/J_1	149.	53.4
i	70°30′	75°40′
r_1	0.418	0.358
r_2	0.075	0.107
$\bar{A}$	14.1	14.1
α_0	1.00	1.00
ρ_1	0.003	0.005
ρ_2	1.17	0.404
π	0″.0024	0″.0017

TABLE V.

NORMALS OF SW OPHIUCHI WITH RESIDUALS FROM COMPUTED UNIFORM CURVE.

Number	Number of Observations	Mean Phase	Mean Magnitude	O—C
1	10	$-0^d.228$	10.18	$-0^m.01$
2	10	.183	10.21	− .03
3	6	.153	10.39	+ .04
4	5	.127	10.50	.00
5	6	.113	10.69	+ .09
6	5	.067	10.95	− .02
7	6	.062	11.08	+ .02
8	5	.049	11.16	.00
9	6	−0.018	11.34	− .03
10	5	+0.009	11.34	− .06
11	7	.031	11.41	+ .11
12	5	.047	11.26	+ .09
13	5	.049	11.06	− .10
14	6	.072	10.84	− .11
15	5	.103	10.64	− .03
16	6	.120	10.61	+ .06
17	6	.142	10.35	− .06
18	7	.174	10.25	− .01
19	10	.198	10.18	− .02
20	11	.224	10.16	− .03
21	10	.261	10.15	− .04
22	10	.284	10.18	− .03
23	11	.333	10.24	+ .05
24	10	.374	10.22	+ .03
25	12	.415	10.21	+ .02
26	11	.459	10.18	− .01
27	10	.507	10.16	− .03
28	11	.534	10.18	− .01
29	10	.586	10.21	+ .02
30	10	.637	10.19	.00
31	10	.674	10.15	− .04
32	11	.719	10.18	− .01
33	10	.749	10.16	− .03
34	10	.790	10.19	.00
35	12	.824	10.26	+ .07
36	13	.869	10.16	− .03
37	10	.893	10.16	− .03
38	12	+0.933	10.26	+0.07

TABLE V—*cont.*

Number	Number of Observations	Mean Phase	Mean Magnitude	O—C
39	10	$+0^d.977$	10.19	$0^m.00$
40	9	1.012	10.18	− .01
41	10	.057	10.18	− .01
42	11	.081	10.21	+ .01
43	10	.108	10.16	− .04
44	10	.137	10.22	+ .01
45	10	.188	10.21	− .01
46	10	.228	10.21	− .01
47	11	.268	10.27	+ .05
48	11	.307	10.21	.00
49	10	.365	10.21	+ .01
50	10	.399	10.24	+ .05
51	10	.433	10.18	− .01
52	12	.462	10.18	− .01
53	10	.506	10.18	− .01
54	12	.565	10.19	.00
55	12	.643	10.18	− .01
56	11	.697	10.19	.00
57	12	.744	10.19	.00
58	10	.793	10.19	.00
59	11	.821	10.18	− .01
60	11	.860	10.19	.00
61	11	.901	10.15	− .04
62	10	.936	10.18	− .01
63	10	1.982	10.18	− .01
64	10	2.023	10.15	− .04
65	10	.061	10.21	+ .02
66	11	.117	10.21	+ .02
67	11	+2.169	10.18	−0.01

TABLE VI.

ORBITAL ELEMENTS OF SW OPHIUCHI.

	Uniform	Darkened
Range, primary	$1^m.22$	$1^m.22$
Range secondary	$0^m.03$	$0^m.03$
t'	$0^d.199$	$0^d.242$
M_1	+2.76	+2.59
M_2	+0.42	+0.25
m_1	12.65	12.65
m_2	10.31	10.31
L_1	0.101	0.101
L_2	0.899	0.899
J_2/J_1	25.5	24.7
i	76° 18′	74° 50′
r_1	0.334	0.354
r_2	0.197	0.212
$\bar{A}$	9.6	9.6
α_0	0.75	0.75
ρ_1	0.016	0.013
ρ_2	0.22	0.17
π	0″.001	0″.001